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TEMPERATURE DISTRIBUTION IN THE HUMAN BODY UNDER VARIOUS
CONDITIONS OF INDUCED HYPERTHERMIA

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16. Abstract A mathematical model based on heat balance equations is developed for studying temperature distribution in the human body under deep hyperthermia. The model yields results which are in satisfactory agreement with experimental data. The distribution of temperature under various conditions of induced hyperthermia, i.e. as a function of water temperature and supply rate, is examined on the basis of temperature distribution curves in various body zones.					
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TEMPERATURE DISTRIBUTION IN THE HUMAN BODY UNDER VARIOUS CONDITIONS OF INDUCED HYPERTHERMIA

O. V. Korobko, T. L. Perel'man and S. Z. Fradkin

There is currently much optimism in oncological practice with regard to a complex therapy involving induced hyperthermia (hyperoxidation) as a means of treating certain forms of malignant tumors. One of the main components of this therapy is hyperthermia, a process in which the human body is heated to 40-42° and kept at this temperature for a prolonged period of time (150-300 minutes). For reasons of safety the temperature of the brain must be kept 1-1.5° lower than the temperature of the body "core" during induced hyperthermia; this is achieved by artificially cooling the head [1, 2].

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For the successful inducement of hyperthermia, it is necessary to know the temperature distribution in the human body during the simultaneous heating of the torso and cooling of the head as well as the dependence of this distribution on the conditions under which the hyperthermia is induced.

To solve the problem of temperature distribution in the human body, we shall utilize the following model. The body is first divided into arbitrary layers (zones), and heat balance equations are set up for each layer. The number of layers (zones) depends on the specifics of the problem at hand and the accuracy with which it must be solved. In our case a four-zone model is sufficient (consisting of the skin, the "core," the brain and the "shell" of the head). Let us further assume that:

* Numbers in the margin indicate pagination in the foreign text.

1) the chief mechanism of heat transfer is convection, resulting from blood flow [3];

2) the blood instantaneously acquires the temperature of the zone in which it is located; and

3) the volume blood-flow rate is a linear function of temperature.

Based on these assumptions, the system of heat balance equations describing the temperature distribution in the human body is as follows:

$$\dot{t}_1 = \frac{1}{m_1 c_1} \{ \alpha_1 S_1 (t_6 - t_1) + G_1 c_7 (t_3 - t_1) - S_1 [4/3 (t_3 - t^*) \beta_3 + 1/3 (t_1 - 33)] \},$$

$$\dot{t}_2 = \frac{1}{m_2 c_2} \{ B_2 [1 + \beta_2 (t_3 - t^*)] - G_1 c_7 (t_3 - t_1) + (G_0 - G_3 - G_4) c_7 (\bar{t} - t_2) \},$$

$$\dot{t}_3 = \frac{1}{m_3 c_3} \{ B_3 [1 + \beta_3 (t_3 - t^*)] + G_3 c_7 (\bar{t}_1 - t_3) - \frac{k S_3}{l} (t_3 - t_4) \},$$

$$\dot{t}_4 = \frac{1}{m_4 c_4} \{ B_4 + G_4 c_7 (\bar{t}_1 - t_4) + \frac{k S_3}{l} (t_3 - t_4) - \alpha_4 S_4 (t_4 - t_6) \},$$

$$\dot{t}_5 = f_1(\tau), \quad \dot{t}_6 = f_2(\tau), \quad \text{where } G_0 = \sum_{i=1}^4 G_i, \quad (1)$$

$$\bar{t} = \frac{1}{G_0} [(G_0 - G_3 - G_4) t_2 + G_3 t_3 + G_4 t_4],$$

$$\bar{t}_1 = \bar{t} - \Delta t, \quad \text{where } \Delta t = \frac{\bar{t} - t_0}{G_3 + G_4} \alpha_3 S_3.$$

The initial conditions: for $\tau = 0$, $t_i = t_i^0$, where $i = 1, 2, \dots, 6$. In deriving equation system (1), it was taken into account that

$$\begin{aligned} G_i &= G_i^0 [1 + d_i (t_i - t^*)], \quad i = 0, 3, \\ G_j &= G_j^0 [1 + d_j (t_j - 33)], \quad j = 1, 4. \end{aligned} \quad (2)$$

The coefficients d_i , d_j and β_i were determined from expression (3):

$$\begin{aligned} \beta_i &= \begin{cases} \beta_i', & \text{if } t_i \geq t^* \\ \beta_i'', & \text{if } t_i < t^* \end{cases} \quad i = 1, 2, 3, \\ d_i &= \begin{cases} d_i', & \text{if } t_i \geq t^* \\ d_i'', & \text{if } t_i < t^* \end{cases} \quad i = 0, 3, \\ d_j &= \begin{cases} d_j', & \text{if } t_j > 33 \\ d_j'', & \text{if } t_j \leq 33 \end{cases} \quad j = 1, 4. \end{aligned} \quad (3)$$

Equation system (1) was solved for specific values of its coefficients with the aid of the "Minsk 22" electronic computer. A comparison of the results obtained with experimental data shows that the model satisfactorily describes the temperature distribution in the human body.

We shall now examine the dependence of temperature distribution dynamics in the human body on the conditions under which hyperthermia is induced.

1. Dependence of temperature distribution in the human body on the temperature of the hot water.

Let the temperature of the water used to cool the head $t_6 = \text{const}$, and let us assume that the coefficients α_1 and α_4 , associated with the rate at which the hot and cold water are supplied to the body and head surface, respectively, are also constant. We shall examine the temperature distribution in the body for various hot-water temperatures t_5 .

Analysis of the temperature distribution curves in Fig. 1 indicates that:

1) the higher the value of t_5 , the higher the temperatures of the different body zones;

2) the higher the value of t_5 , the more time is required for the system to achieve a steady state;

3) for any value of t_5 , the inequality $t_4 < t_3 < t_2 < t_1 < t_5$ is satisfied in the steady state;

4) the temperature difference between the different body zones (for large values of τ) depends only very slightly on the value of t_5 .

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Thus, by changing the hot-water temperature t_5 we change only the absolute value of the temperatures in the various zones but effect practically no change in the relative temperatures of the zones.

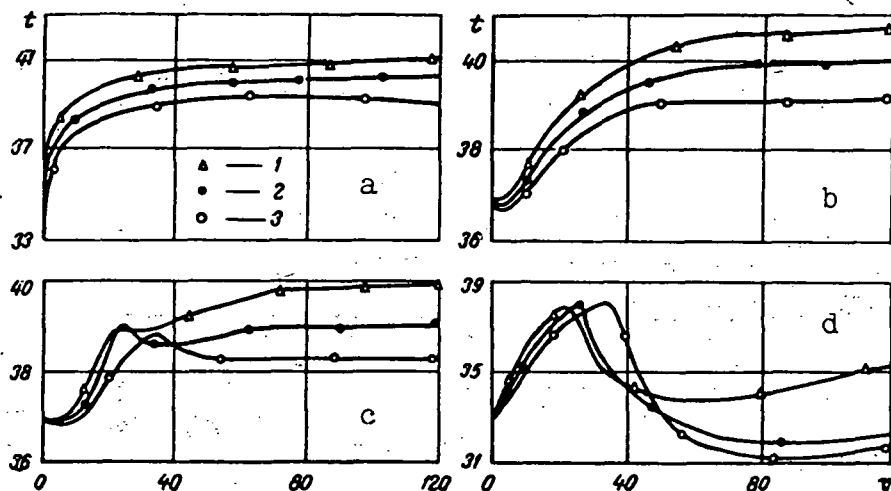


Fig. 1. Temperature distribution in the human body as a function of hot-water temperature: a - in skin; b - in body core; c - in brain; d - in head shell; 1 - $t_5 = 42^\circ$; 2 - 41° ; 3 - 40° .

2. Temperature distribution in the human body for various values of the coefficient α_1 .

Let the temperature $t_5 = \text{const}$, $t_6 = \text{const}$ and the coefficient $\alpha_4 = \text{const}$. We shall examine the dependence of the temperature distribution on the value of the coefficient α_1 , which is a function of the supply rate of heated water to the body surface (Fig. 2).

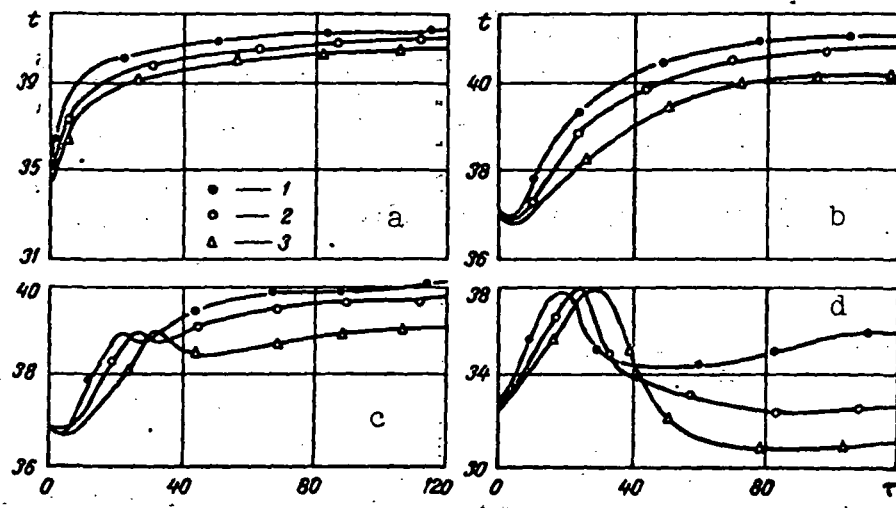


Fig. 2. Temperature distribution in the human body as a function of the value of the coefficient α_1 : a - in skin; b - in body core; c - in brain; d - in head shell; 1 - $\alpha_1 = 1.8$; 2 - 1.2; 3 - 0.8.

As Fig. 2 shows, the higher the value of α_1 , the more rapidly the system achieves a steady state. Since artificial cooling of the head was begun only at $t_3 \geq 39$, the curves (Fig. 2, c and d) are shifted to the right. This is entirely reasonable if we consider that the rate of temperature rise in the body zones increases with the value of the coefficient α_1 .

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3. Dependence of the temperature distribution in the human body on the temperature of the water cooling the head.

Let us assume that the temperature t_5 and the coefficients α_1 and α_4 are constant. We shall consider the dynamics of temperature distribution in the body as a function of the temperature t_6 of the water used to cool the head (Fig. 3).

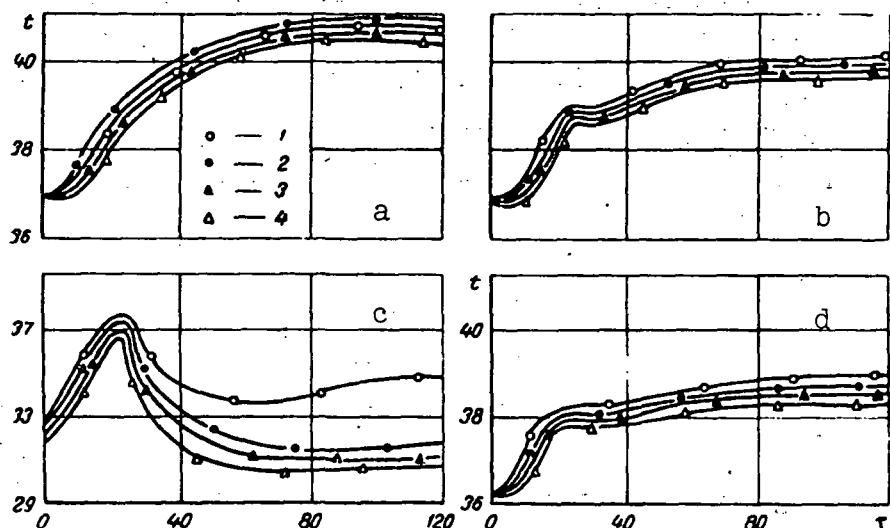


Fig. 3. Temperature distribution in the human body as a function of the temperature of the water cooling the head: a - in the body core; b - in the brain; c - in the head shell; d - in the region of the tympanic membrane; 1 - $t_6 = 6^\circ$; 2 - 4° ; 3 - 2° ; 4 - 0.5° .

Fig. 3 shows that a change in t_6 has practically no effect on temperature dynamics in the core (Fig. 3, a) or the skin (not shown in Figure). Moreover a change in t_6 under conditions of general hyperthermia has no significant effect, based on the mathematical model, on the temperature of deeper brain layers (Fig. 3, b) and mainly affects the temperature of its more superficial layers (the "head shell"¹) [Footnote next page]. These

results are of practical importance. First, brain-temperature determinations are frequently based on the temperature in the region of the tympanic membrane. It can be shown that this temperature, \bar{t} , is the resultant between the brain temperature t_3 and the head-shell temperature t_4 , i.e., $\bar{t} = n_1 t_3 + n_2 t_4$, where $n_1 < 1$, $n_2 < 1$.

Hence, a temperature drop in the region of the tympanic membrane (Fig. 3, d) apparently does not imply a commensurate drop in the temperature of the brain.

Second, the weak correlation between brain temperature and the temperature of the cooling water makes excessive cooling of the water unnecessary, thereby simplifying the apparatus involved. Third, a serious effort should be made to develop methods enabling a higher temperature gradient to be established between the body core and the brain during hyperthermia (by cooling the neck, for example).

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4. Temperature distribution in the human body for various values of the coefficient α_4 .

Assume that the temperatures t_5 and t_6 and the coefficient α_1 are constant. Let us examine the dependence of the temperature distribution in the body on the value of the coefficient α_4 , which reflects the supply rate of cooling water to the head (Fig. 4).

As Fig. 4 shows, a change in α_4 effects practically no change in the core temperature (Fig. 4, a) or the skin temperature (not shown in Figure). The brain temperature undergoes appreciable changes, although in this case they are smaller than the temperature changes in the region of the tympanic membrane would suggest.

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1. The "brain" and "head shell" zones were arbitrarily selected. Our results therefore require thorough investigation and experimental corroboration.

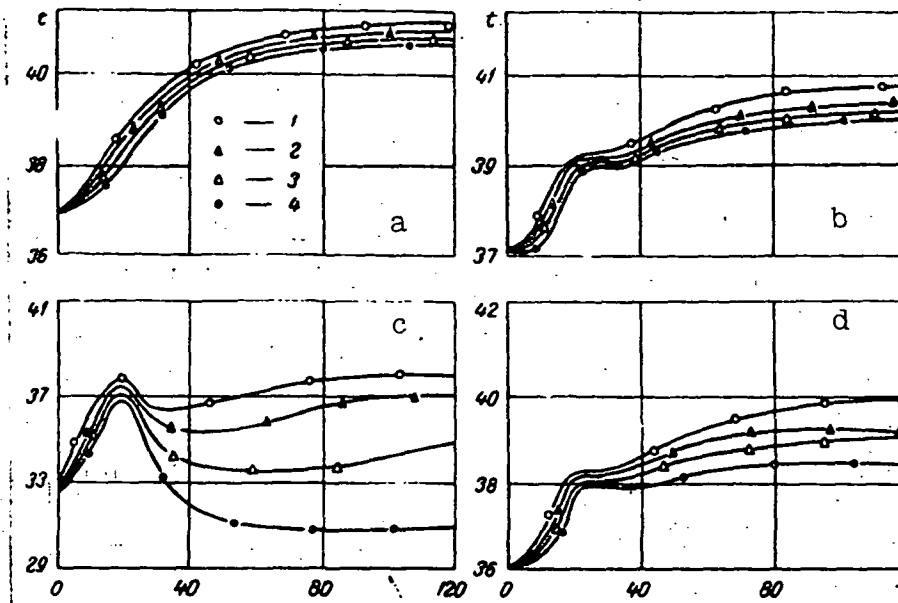


Fig. 4. Temperature distribution in the human body as a function of the value of α_4 : a - in the body core; b - in the brain; c - in the head shell; d - in the region of the tympanic membrane; 1 - $\alpha_4 = 0.6$; 2 - 0.8; 3 - 1.0; 4 - 1.2.

A comparison of the results presented in sections 3 and 4 indicates that a change in the value of the coefficient α_4 , i.e. a change in the rate of cooling-water supply to the head surface, is a more efficient means of lowering the brain temperature than a decrease in the temperature of the cooling water. Since the core temperature (for sufficiently high values of α_1) is affected little by a change in α_4 , the temperature gradient $\Delta t = t_2 - t_3$ is increased, leading to significant practical benefits.

Thus, by varying the temperature t_5 we can regulate the level of the steady state in the human system. By varying the coefficient α_1 , we can strongly influence the time needed to achieve this level; and by varying α_4 we can regulate the temperature gradient between the different zones of the body.

Nomenclature

$\dot{t} = \frac{dt}{dt}$, t , temperature ($^{\circ}\text{C}$); t^* , standard temperature ($^{\circ}\text{C}$);
 m , mass (kg); c , specific heat (J/kg \cdot deg); G , mass blood-flow rate
(kg/s); α , coefficient of heat transfer between surface and
transfer medium (W/m² \cdot deg); k , thermal conductivity (W/m \cdot deg);
 B , basal metabolism (W); S - surface area (m²); ℓ , thickness of
the "head shell" (m); the subscripts 1, 2, 3, 4, 5, 6, 7, 8, 9
refer to the skin, core, brain, head shell, hot water, cold water,
blood, neck and air, respectively.

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